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PAPER THROUGH IMPULSE DRYING**

HUGH P. LAVERY

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New Mechanisms for Water Removal from Paper
Through Impulse Drying

Hugh P. Lavery
Research Associate and
Assistant Professor of Engineering
The Institute of Paper Chemistry
Appleton, WI 54912

ABSTRACT

The typical dewatering processes used in papermaking, wet pressing and hot surface drying, have been improved significantly over the past decade. However, the fundamental mechanisms of these processes offer limited further opportunities for large gains in process performance. New water removal mechanisms must be developed to support the industry's need for reduced capital and operating costs.

Impulse drying is a new process for removing water from a moist web by passing the web through a press nip with one very hot roll. When applied to wet sheets in the 25 to 50% solids range, impulse drying produces water removal rates about twice those found in conventional wet presses. Above 50% solids, impulse drying removes water 500 to 1000 times faster than conventional cylinder drying at similar sheet solids levels. These dramatic improvements in water removal result from the application of a new mechanism, vapor displacement, to the problem of web water removal.

When a moist web is applied with sufficient pressure to a hot roll surface, steam is generated rapidly near the heated surface of the sheet. The expanding steam acts to displace liquid water from the sheet rapidly and with much lower energy consumption than purely evaporative drying. This paper presents evidence for this novel water removal mechanism drawn from recent studies on wet linerboard sheets (15 to 65% solids). These data permit a comparison between impulse drying and wet pressing in terms of water removal performance and dewatering mechanisms.

KEYWORDS: Pressing, Drying, Water Removal, Linerboard

INTRODUCTION

Impulse drying may be defined as the use of a long press nip with one very hot roll to remove water from a wet paper web. Impulse drying combines the mechanical compression found in wet pressing with high-temperature hot surface drying. The effectiveness of combining elevated temperature and pressure to remove water from paper was first reported by Wahren (1). Recent research has explored nip pressures in the 4 to 5 MPa range and hot surface temperatures from 175° to 400°C for nip residence times of 15 to 100 milliseconds. This range of conditions could be achieved in a long nip press with the addition of an external heater on the roll which contacts the web.

The mechanisms and performance potential of impulse drying have been studied extensively at The Institute of Paper Chemistry over the past two years. Burton (2), Sprague and Burton (3) and Burton and Sprague (4) described the vapor displacement mechanism as observed in 42% solids bleached kraft sheets. Comprehensive reports by Sprague (5) and by Lavery (6) summarized the early work on water removal, energy use, and physical properties development during impulse drying. All of these studies tested relatively dry sheets to compare the performance of impulse drying with conventional cylinder drying. The goal of the study reported here was to collect mechanistic data from much wetter sheets than previously studied to evaluate impulse drying as a substitute for wet pressing. One commercially significant furnish, never-dried virgin kraft linerboard, was tested. The response of this furnish to impulse drying has been otherwise well characterized (6).

EXPERIMENTAL

A variety of experimental techniques was used in this study to simulate impulse drying on the bench scale and to measure heat transfer, water removal, and web compression histories. Most of these techniques are complicated and involve the use of custom-built equipment. Only a brief summary of the various techniques can be provided here; more detail can be obtained from the references cited in each section.

Equipment

A bench-scale impulse drying simulator (6) was used in this study. The simulator is an electrohydraulic press with its upper platen heated by electrical cartridge heaters, as shown in Figure 1. The simulator electronic controls allow a wide range of pressure-time profiles to be produced easily and reproducibly. Haversine pressure pulses were generated for all tests reported here. A load cell above the upper platen is used to control and measure the total load and the pressure profile. The surface temperature of the upper platen is controlled using the signal from a surface junction thermocouple. A presteaming ring can be added to the system to preheat the sheets prior to impulse drying.

(Figure 1 here)

Handsheets and Furnish

Handsheets were formed according to TAPPI standard procedures, except that the sheet diameter was reduced to five inches to permit high pressure drying within the force limits of the electrohydraulic press system. A virgin kraft, never-dried unbleached softwood pulp obtained from a southern U.S. linerboard mill was used for these experiments. The pulp was lightly refined to 730 ml CSF, and formed to a 125 g/m² basis weight. Sheets were couched and stored in sealed plastic bags until needed, but

were not held for longer than two days. The target moisture content before impulse drying was reached by pressing the sheet in a laboratory roll press using press impulse levels typical of commercial equipment.

Dynamic measurement of sheet thickness

The dynamic change of sheet thickness in response to the applied pressure pulse was measured using a method developed in its present form by Burton (2). Eddy current displacement transducers mounted in the bottom pedestal of the bench impulse drying simulator were used to follow the motion of small copper mesh targets embedded in handsheets. The targets were dynamically formed into the handsheets, using a special sheet mold originally described by Cowan (7). The small dimensions (0.0254 mm in thickness) and 65% open area of the copper mesh helped secure good integration of the targets into the sheet structure. The general arrangement of the transducers and targets is shown in Figure 2. Targets were positioned at the top and bottom surfaces of the sheet, and inside the sheet at levels corresponding to one-quarter and three-quarters of the total caliper of the sheet. The apparent void fraction of the region of the sheet between any two targets can be calculated from the caliper information as follows:

$$\text{Void Fraction} = (\text{Total Caliper} - \text{Fiber Caliper}) / (\text{Total Caliper})$$

$$\text{Fiber Caliper} = (\text{Basis Weight} / \text{Density}) / (\text{Fraction of sheet thickness between targets})$$

A fiber solids density of 1.5 grams per cubic centimeter was assumed in the void fraction calculation. An initially uniform distribution of fiber through the sheet was also assumed in these calculations.

(Figure 2 here)

Sheet internal temperature measurement

Temperatures at various positions within the sheet were measured by placing fine-gage (0.025 mm) thermocouples between the layers of handsheets built up of multiple plies. The thermocouples were spaced one-eighth, one-third, two-thirds, and seven-eighths of the way through the sheet thickness. The composite sheet was then pressed to the target moisture content and impulse dried. The signals from the thermocouples were recorded by a high-speed Tracor Northern TN-1710 data acquisition system.

Liquid water removal measurement

The proportions of water removed from the sheet in the liquid and vapor phases were measured by a salt tracer technique developed by Devlin (8). The method begins by saturating the adsorption sites on the pulp fibers with aluminum nitrate to minimize subsequent adsorption of the tracer salt, lithium chloride. Handsheets are then formed from a dilute aqueous solution of aluminum nitrate and lithium chloride. Next, the sheets are impulse

dried as described above. The lithium chloride content of the felt is then measured by extracting the felt in boiling water and analyzing the extract for its lithium content by flame emission spectroscopy. Any lithium found in the felt was carried there only by liquid water. The liquid water flow into the felt can be calculated from the initial concentration of lithium in the water used to form the handsheet.

Heat flux measurement

The instantaneous heat flux from the metal platen into the web was measured using a technique originally developed for ballistics applications (9). The temperature history of the metal surface is measured by means of a surface junction thermocouple. The heat flux from the metal surface required to produce the observed temperature history is then deduced from the temperature measurements by assuming that the metal mass acts as a semi-infinite slab initially at a constant temperature. A FORTRAN computer program on a Burrough B6900 mainframe is used to perform the computationally intensive heat transfer modeling.

RESULTS AND DISCUSSION

Impulse drying represents the addition of a new variable, hot roll temperature, to the familiar papermaking process of wet pressing in a long-nip press. Wet pressing acts to remove water

principally through a volume-reduction mechanism (10). Water flows from the sheet into a water receiving felt in response to a hydraulic pressure gradient which develops as the sheet is compressed. Although the process of compressing a web to drive out water appears simple, DeCrosta (11) has compiled a list of almost forty process variables which have been found to be significant in the commercial application of wet pressing. Long nip press technology was developed to enhance the range of one of the principal variables, press impulse, by extending the time available for water to flow from the sheet.

Water removal in a press nip is strongly influenced by the temperature of the web. Andersson and Back (12) have shown that the outgoing dryness can increase by eight percentage points if the web temperature is increased from 5 to 90°C. Increasing temperature in this range acts to improve wet pressing performance both by reducing the viscosity of water and by softening the fibers to promote web compressibility. Similar effects are observed as the roll surface temperature is increased toward 100°C. Figure 3 illustrates the effect of increasing the hot surface temperature on the final percent solids achieved in a 25 millisecond nip at 4.7 MPa peak pressure starting from a sheet solids content of 35%. As hot surface temperatures are raised toward 100°C, final percent solids achieved will climb gradually into the 38 to 42% solids range.

(Figure 3 here)

Over 100°C, the percent solids out of the nip increases rapidly with further increases in hot surface temperature. At 300°C, impulse dried linerboard sheets can reach 60% solids. However, a portion of this temperature range is not usable in practice. Sheet adhesion to the hot surface has been a problem between 120 and 175°C, limiting useful data from those conditions. Impulse drying is therefore studied in the surface temperature range above 175°C, where sticking is no longer evident.

Increasing hot surface temperatures into the impulse drying regime does more than simply enhance the action of wet pressing through reducing the viscosity of water. The water removal performance of impulse drying and wet pressing differ in several important respects. First, impulse drying is much less dependent on sheet moisture content than wet pressing. Figure 4 presents a comparison between the sheet dryness after the nip achieved by wet pressing at 30°C with a peak pressure of 4.7 MPa for 30 milliseconds and the results of impulse drying under the same nip conditions but at a hot surface temperature of 315°C. Wet pressing water removal was much less effective than impulse drying under these conditions, and was much more dependent on sheet moisture content. Impulse drying water removal is only slightly dependent on sheet ingoing percent solids over the range

from 15 to 50% solids. The final sheet solids level was approximately 58% solids over that range of conditions. In addition, the water removal ability of wet pressing was exhausted by about 45% solids, while impulse drying was able to continue to remove water from sheets as dry as 75% solids.

(Figure 4 here)

The substantial differences in impulse drying and wet pressing performance shown in Figures 3 and 4 suggest that some mechanism is at work in impulse drying beyond the usual web volume reduction process of wet pressing. A likely new mechanism is the displacement of liquid water by steam formed near the interface between the sheet and the hot metal surface. The amount of steam produced during impulse drying can be estimated using the lithium chloride tracer technique outlined above. The tracer technique measures the amount of liquid water received by the felt, while the total amount of water removed from the sheet is measured gravimetrically. The amount of steam formed during impulse drying can be calculated as the difference between the total water removal and the liquid phase water removal.

The results of lithium chloride tracer studies (Figure 5) show that approximately 0.025 kg of steam is produced in each square meter of paper at all sheet moisture contents between 25 and 65% solids when 125 grams per square meter linerboard sheets

are impulse dried for 30 ms at 4.7 MPa and 315°C. The steam necessary for a vapor displacement mechanism is, therefore, present at some point during the impulse drying event.

The amount of liquid water displaced by this steam is a strong function of sheet moisture content. At 65% solids, about 30 percent of the mass of water removed is removed as liquid, but at 25% solids over 80 percent of the water is removed as liquid. This response would be expected in a displacement mechanism. This mechanism can only be effective as long as there are no paths for vapor to escape from the sheet except by displacing water. Drier sheets increase the possibility of local water-depleted regions through which vapor could escape into the water receiver without also removing water.

However, even relatively dry sheets exhibit excellent water removal performance compared with conventional papermaking processes. At 42% solids, a total of 0.1 kg water was removed from each square foot of paper, corresponding to a water removal rate of 12,000 kg per hour per square meter. Conventional cylinder drying, which would usually begin for this grade at about 42% solids, has a typical water removal rate of 25 kg per hour per square meter for linerboard. The rate of water removal in impulse drying is thus 480 times that of conventional cylinder dryers under these conditions. Eighty-five percent of that water is

displaced rather than evaporated, leading to savings in energy from impulse drying rather than conventionally drying. These high water removal rates with substantial liquid phase water removal again point toward a vapor displacement mechanism.

Very wet sheets below 25% solids content display an increase in steam production, as may be seen in Figure 5. This effect may be due to an increase in water availability at the sheet surface. Sheets impulse dried above 25% solids may reach a limit in the water supply available near the sheet surface before other process limits take effect.

(Figure 5 here)

The steam production data in Figure 5 do not provide information on when the steam is formed during the nip loading. However, measurement of the instantaneous heat flux from the hot metal surface into the sheet shows that the peak heat flux occurs early in the nip, well before peak pressure is achieved (Figure 6). The peak heat fluxes observed are of the same magnitude as those reported for pool boiling heat transfer (13). It thus seems probable that the peak heat flux occurs in conjunction with the production of steam and so with the major portion of the liquid displacement process. The decline in heat flux which, in Figure 6, begins before the peak pressure is reached probably reflects a limitation in the amount of water available near the surface.

(Figure 6 here)

The temperature history through the sheet thickness, Figure 7, also supports the formation of a steam layer near the hot surface of the sheet. The temperature at the one-eighth basis weight point measured from the hot surface rapidly reaches temperatures above 100°C , which persist until the end of the nip. Peak temperatures in this hot region reach 180°C about two-thirds of the way through the nip. However, temperatures at the middle and the cool side of the sheet rise more slowly and do not reach the levels observed on the hot side of the sheet. The back one-eighth of the sheet reaches 100°C only at the end of the nip. It is, therefore, not likely that steam is present throughout the sheet until late in the nip.

(Figure 7 here)

The decline in temperature as pressure decreases after mid-nip is probably due to water flashing from fine pores in the sheet structure and condensing in the cooler regions of the sheet. In Figure 7, the three thermocouples closest to the hot side of the sheet all register declines in temperature after mid-nip, even though the sheet is still under restraint and continuing to receive heat from the metal surface, as may be seen by comparing the heat flux data in Figure 6. This rapid exchange of heat between the hot side of the sheet and the cooler back side again

indicates a vapor-filled region to support intense evaporation/condensation heat transfer across the sheet.

The differences in water removal mechanisms between wet pressing and impulse drying are also apparent in the internal deformations of the sheet. Wet pressing removes water by web compression, which causes a reduction in the void fraction of the sheet and expulsion of the water and air which may be occupying the voids. A typical plot of the void fraction history during a wet pressing event as calculated from internal sheet caliper data is shown in Figure 8. For this 35% solids sheet, the web will reach saturation at a void fraction of 0.74; the void fraction at the end of the nip (0.7) agrees with the gravimetrically measured 40% solids. The void fraction profile through the sheet reflects sheet stratification due to shear forces compacting the fibers on the water-receiver side of the sheet, a phenomenon which has been described in detail by MacGregor (14).

(Figure 8 here)

In contrast, the impulse dried sheet shows a rapid decrease in void fraction in the 25% of the sheet thickness nearest to the hot surface early in the nip (Figure 9). This decrease in void fraction occurs at the same time the peak heat flux and surface layer temperature are increasing. The lower 75%

of the sheet thickness is much less compacted than during the corresponding wet pressing event (Figure 8) and, in fact, is compressed to void fractions only slightly lower than saturation. These data suggest that liquid water is evaporating from the large voids in the region of the sheet near the hot surface, accompanied by the compression of the sheet structure as steam leaves the region. The cooler portion of the sheet experiences liquid water flow in response to the vapor generation, with only a small reduction in void fraction.

(Figure 9 here)

The upper 25% of the sheet experiences a final reduction in void fraction at the end of the nip, probably due to flashing of superheated water from very small pores in the sheet. The flashing effects the collapse of the fine structure of fibers near the hot surface of the sheet, and contributes to the decline in temperature observed in Figure 7. At the end of the nip, the sheet has been stratified with a dense layer near the hot surface and relatively bulky material in the middle and the cold side of the sheet. This density profile can have important consequences in developing the strength properties of the sheet (6), in addition to providing evidence for the presence of new dewatering and densification mechanisms during impulse drying.

CONCLUSIONS

Impulse drying can achieve very high rates of water removal, in excess of twice the rates for wet pressing under many conditions. This water removal performance appears to result from new water removal mechanisms induced by the presence of one very hot pressing surface during impulse drying. The evidence from experiments to measure liquid water removal, heat flux into the sheet, sheet internal temperatures, and sheet void fraction changes support the concept that steam is generated rapidly early in the nip due to boiling in the sheet near the hot surface. The steam moves through the sheet toward the water receiver, displacing liquid water from the lower regions of the sheet. The combination of vapor generation and liquid displacement also promotes the development of a unique structure in the sheet, with a densified layer adjacent to the hot surface and a bulky middle and cool side which have not had to be densified to express water from the sheet.

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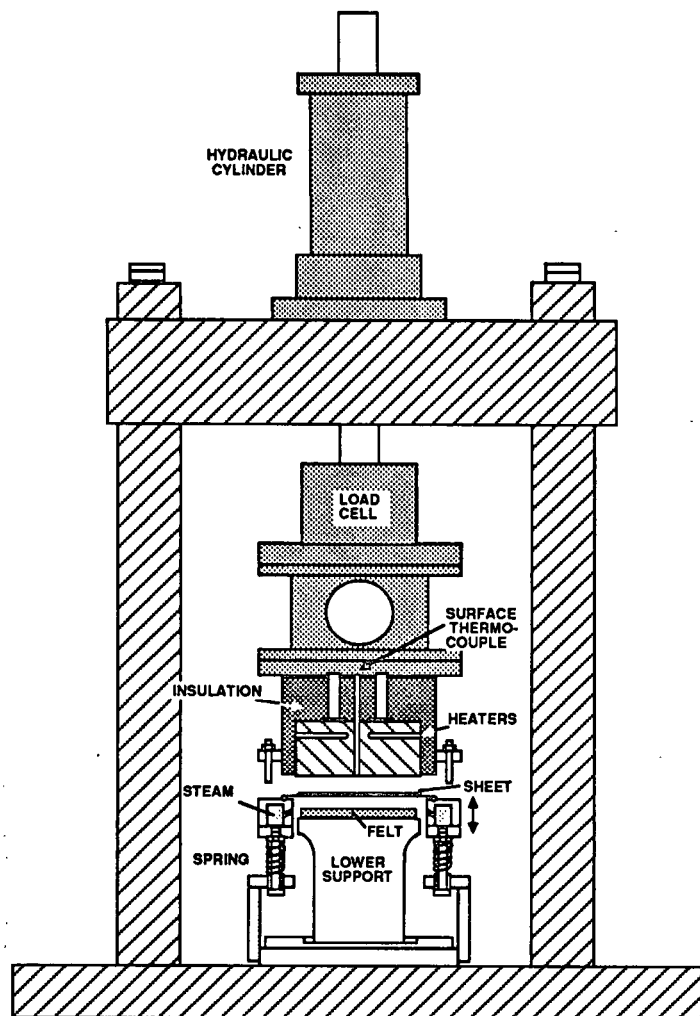


Figure 1. Electrohydraulic press simulator with impulse drying head and presteaming ring installed.

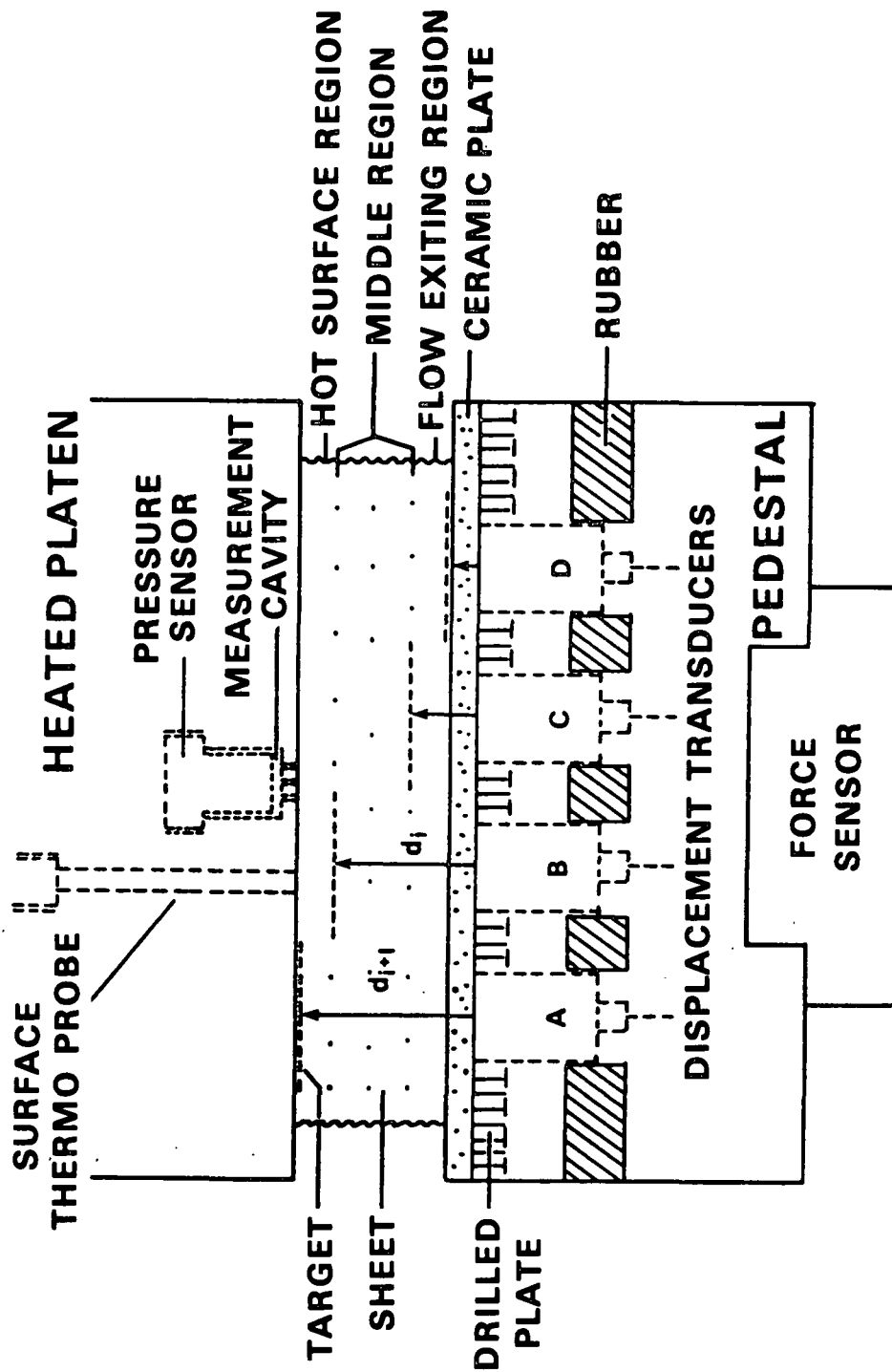


Figure 2. Sensor head design for measuring dynamic changes in sheet thickness during impulse drying (2).

TEMPERATURE EFFECTS ON WATER REMOVAL

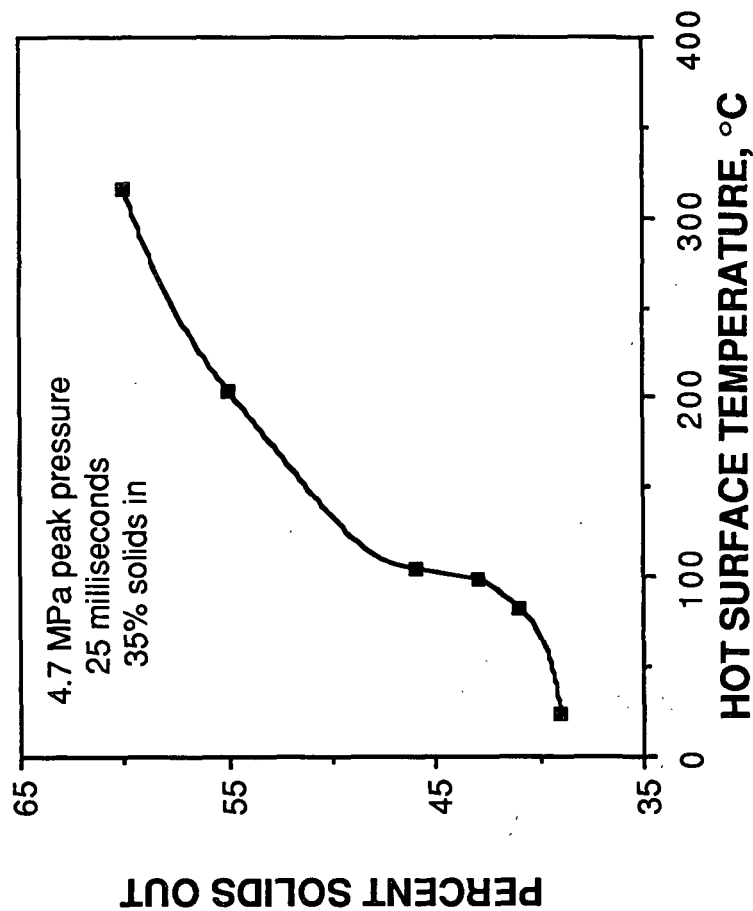


Figure 3. The effects of hot surface temperature on water removal from a moist paper web originally at 25°C. Virgin kraft linerboard at 125 grams per square meter basis weight, initially at 35% solids.

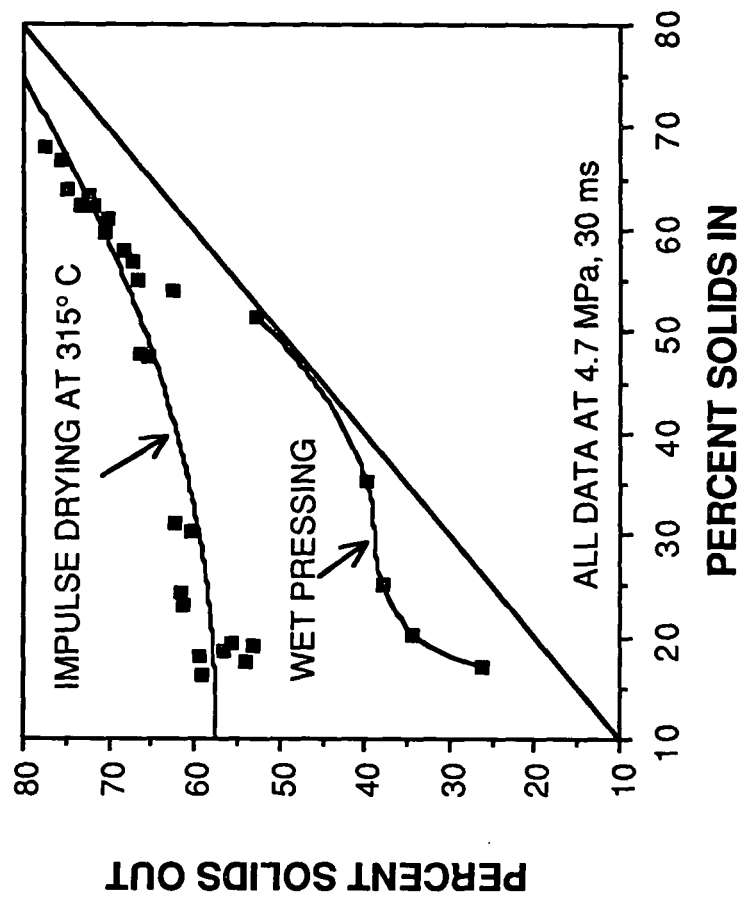


Figure 4. A comparison between the final sheet percent solids achieved by impulse drying and conventional wet pressing. Virgin kraft linerboard at 125 grams per square meter, pressed at 30°C by applying a haversine pulse with 4.7 MPa peak pressure for 30 ms. Impulse drying conditions duplicated press conditions, but with the hot surface at 315°C. All sheets presteamed to 75°C.

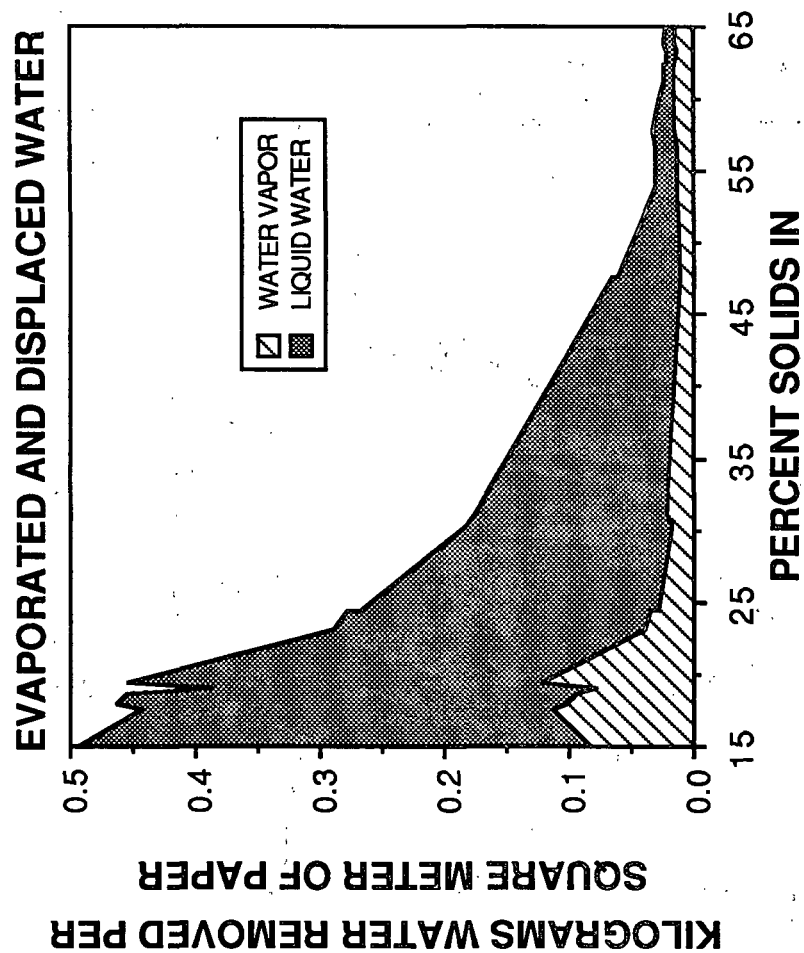


Figure 5. Water removal in liquid and vapor phases during impulse drying as determined by the lithium chloride displacement technique (8). Virgin kraft linerboard at 125 grams per square meter, impulse dried at 315°C by applying a haversine pulse with 4.7 MPa peak pressure for 30 ms. All sheets presteamed to 75°C.

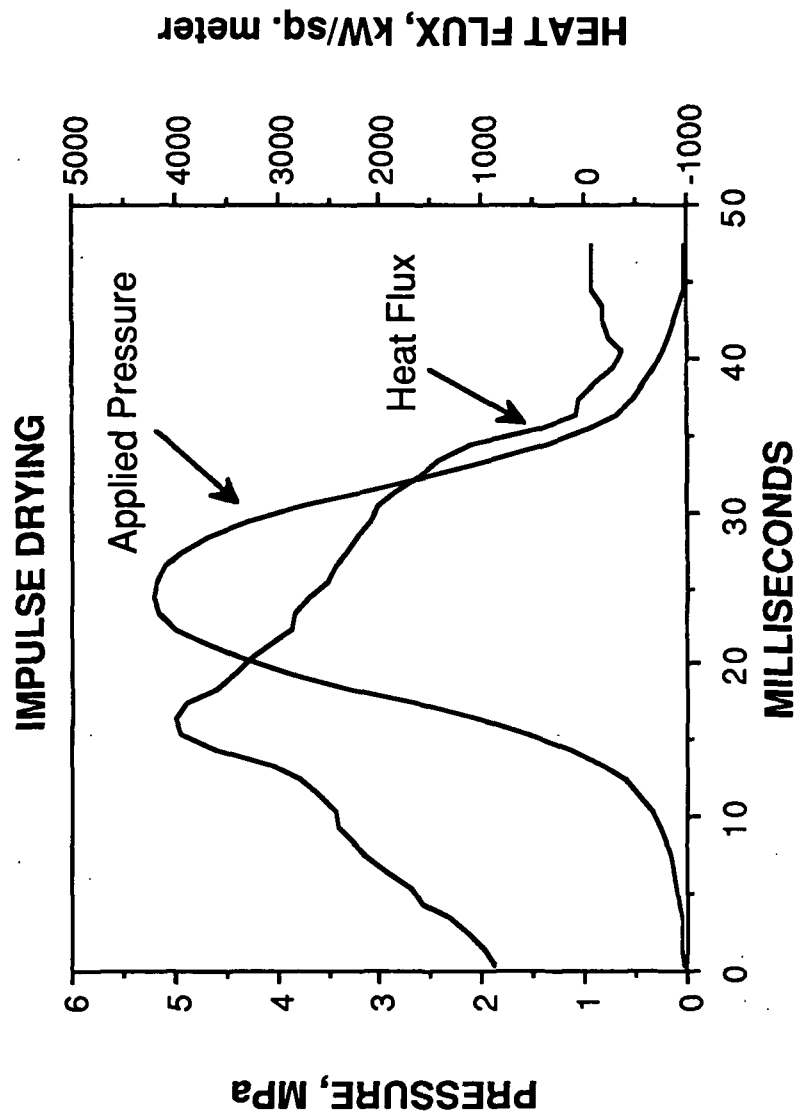


Figure 6. Instantaneous heat flux observed during impulse drying of a 125 grams per square meter virgin kraft linerboard sheet initially at 35% solids and 75°C using a hot surface temperature of 315°C.

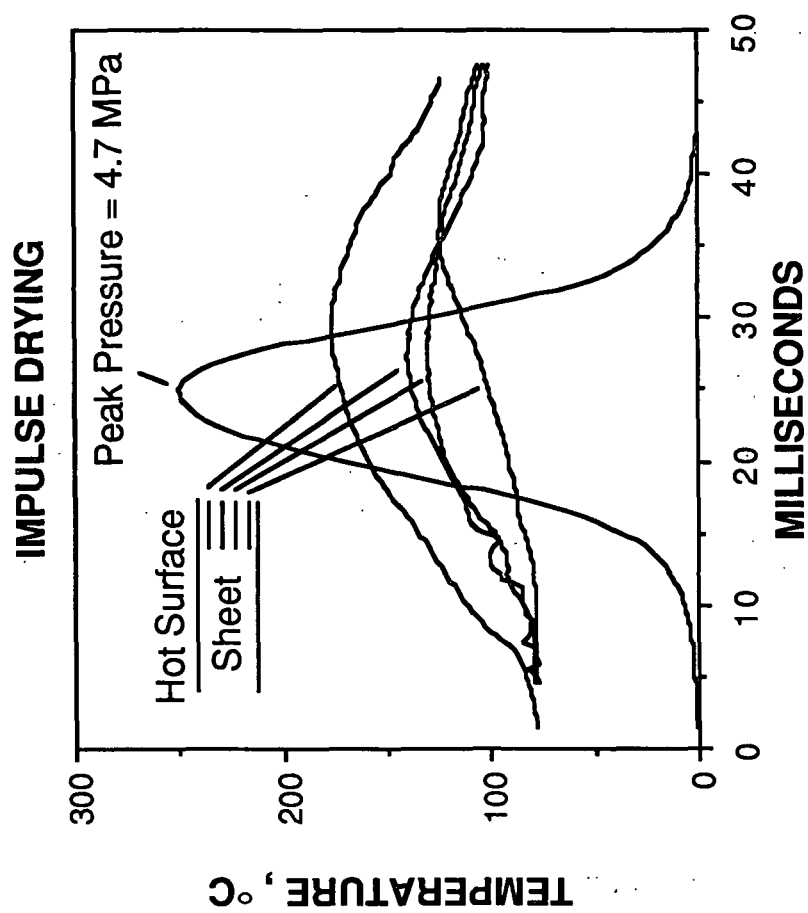


Figure 7. Sheet temperature profiles measured by in-sheet thermocouples during impulse drying of a 125 grams per square meter virgin kraft linerboard sheet initially at 35% solids and 75°C using a hot surface temperature of 315°C.

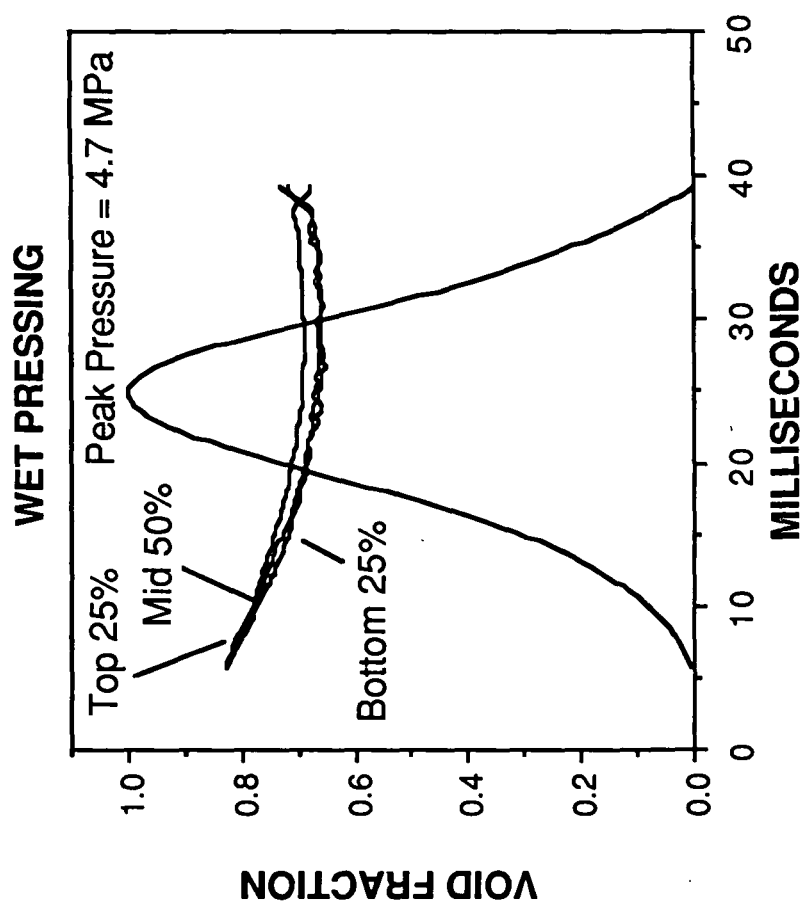


Figure 8. Void fraction changes during wet pressing calculated from caliper data measured by the eddy current transducer/copper mesh target technique (2). Wet pressing at 30°C of a 125 grams per square meter virgin kraft linerboard sheet initially at 35% solids using a haversine pulse with a peak pressure of 4.7 MPa.

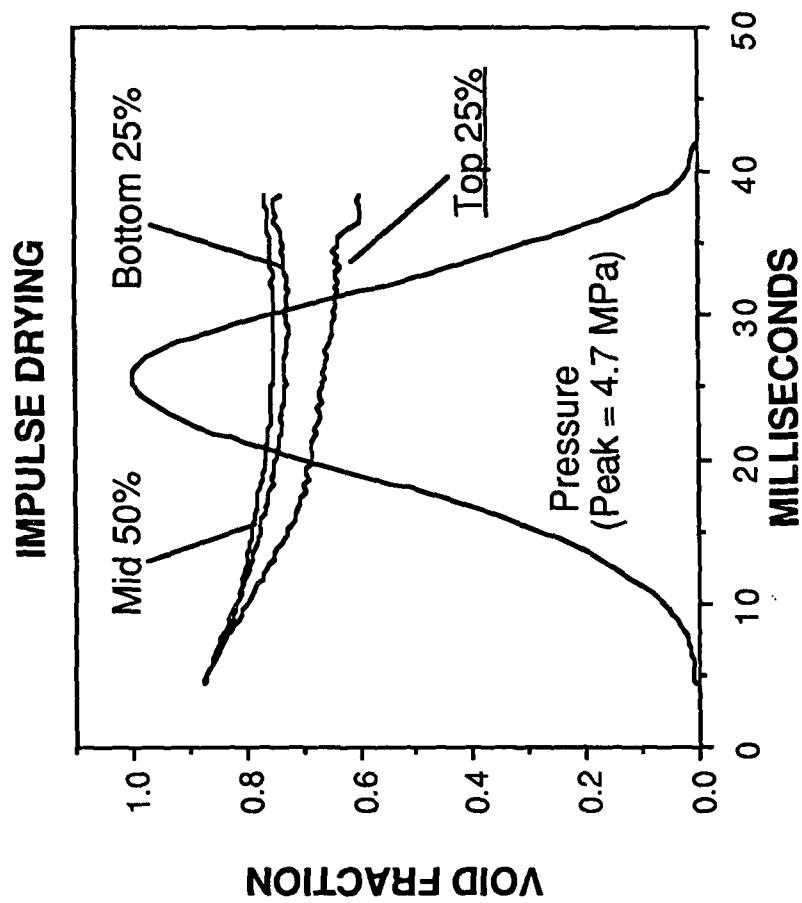


Figure 9. Void fraction changes during impulse drying at 315°C, calculated from caliper data measured by the eddy current transducer/copper mesh target technique (2). Data are for a 125 grams per square meter never-dried, virgin kraft linerboard sheet initially at 35% solids and 75°C, impulse dried using a haversine pulse with a peak pressure of 4.7 MPa.